NASA TECHNICAL TRANSLATION NASA TT F-15,875

OPHTHALMOLOGICAL PROBLEMS IN SPACE FLIGHTS

G.B. Bietti

Translation of "Problemi oftalmologici nel volo aerospaziale," Bollettino d'Oculistica, Vol. 49, No. 2, 1970, pp. 91-101

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 AUGUST 1974

STANDARD TITLE PAGE

1. Report No. NASA TT F-15,875	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle OPHTHALMOLOGICAL PROBLEMS IN SPACE FLIGHTS		5. Report Date August 1974
		6. Performing Organization Code
7. Author(s) G.B. Bietti, Director, Eye Clinic, Rome University		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates, P.O. Box 5187 Redwood City, California 94063		11. Contract or Grant No. NASw-2481
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, WASHINGTON, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Problemi oftalmologici nel volo aerospaziale," Bollettino d'Oculistica, Vol. 49, No. 2, 1970, pp. 91-101.

16. Abstract

Ophthalmological problems have a prominent place in all aspects of flight; in this article, the author reviews some of the major ophthalmological problems met in the field of aviation and space medicine, such as: hypoxia, barometric depression, the effects of acceleration and supersonic speeds, vibrations, air drafts and external temperature, as well as devoting a considerable amount of space to various problems dealing with illumination (dazzling, night flights, various types of irradiations, color distinction, etc.).

17. Key Words (Selected by Author(s))		18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 13	22. Price

NASA-HQ

OPHTHALMOLOGICAL PROBLEMS IN SPACE FLIGHTS

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The importance of eyesight has understandably aroused the /91*
attention of scientists, technical people and pilots, ever since the dawn of aviation.

Investigations of the behavior of the organs concerned with sight in relation to flight thus began very early and have continued uninterrupted to the present day. The direction of this research has undergone changes, in order to relate to the progress of flight, atmospheric, stratospheric, and in space.

At first, attention was paid especially to the effects of hypoxia. Work done on man in flight and in the laboratory, using a depression chamber or inhalation of oxygen-poor mixtures, has shown that hypoxia has many effects on the sight apparatus. These include changes in the senses, circulatory disturbances, eye mobility disturbances (intrinisic and extrinsic), and changes of the transparency of the media of the eye.

I shall not go into details of the results of these investigations, on which I have in the past repeatedly reported, with many personal contributions and contributions from my coworkers. I shall only remark that hypoxia causes mainly a lowering of the retina's sensitivity, especially in regard to physiological scotomatous formations present in the normal person, and a lowering of light sensitivity, noticeable already at moderate altitudes. This is differentiated from the central visual acuity and color sensitivty, which are only moderately influenced by /92
hypoxia.

*Numbers in the margin indicate pagination in the foreign text.

Circulatory changes due to hypoxia reflect those of the general circulation, although they have some specific aspects, such as the slight increase in ocular tonus, the purplish look of retinal arteries, the changes in the endo-ophthalmoscopic picture, the increase of permeability of the hemo-ophthalmic barrier, the increase of pressure in the carotid circulation, and of the ophthalmic [circulation] in most cases.

Changes of the intrinsic and extrinsic eye musculature are especially important. Besides specific disturbances of the pupil and of accommodation (increased distance of the punctum proximum), disturbances of muscular balance must be emphasized. There is a tendency toward exophoria for distant vision and esophoria for near vision, the appearance of vertical imbalances, decrease of fusion capability, and amplitude, disturbances of coordinated eye movements, as in reading.

Changes in transparency due to hypoxia are mainly due to temporary clouding of the crystalline lens, which, however, is only of experimental value.

I also wish to emphasize the fact that pre-existing ocular changes may suffer serious worsening through oxygen deficiency.

Besides hypoxia, also barometric depression in fast ascents to great heights has been studied; this can lead, through the development of small nitrogen bubbles in the blood, to gas embolism of the eye, with the appearance of scotomata. In explosive decompression, which mostly occurs in flight accidents, the eyeball, peculiarly, is often spared, perhaps due to the remarkable stability of ocular tension. Orbital hemorrhages with exophthalmos are, however, observed.

Since the time when high flight speeds were first attained, the importance of acceleration has been noted. These effects are of increasing interest, as the speeds increase, contrary to what happens with hypoxia, whose practical significande has greatly decreased with the use of oxygen inhalators and of pressurized cabins.

Acceleration causes very peculiar manifestations in the eye. The retinal circulation is affected by the displacement of the body's blood mass in the direction of the inertial reaction. /93

In the so-called head-feet (or $+G_z$) acceleration; a gradual blackout takes place. This was already known to the pilots of the 1927 Schneider Cup; it takes place while the subject is still fully conscious; he becomes unconscious only later, if the acceleration persists or increases.

The priority of the eye disturbances (which take place even at accelerations from 4 to 6 g) relative to cerebral disturbances is due to the earlier ischemia of the retinal vessels, which are already partially compressed by the existing tonus of the eye, whence their collapse before that of cerebral vessels.

With negative acceleration, feet-head (or $-G_z$), the so-called "red vision" is experienced, due to retinal and blood repletion.

It is unnecessary to emphasize that, with the increase of speed, changes in direction cause even larger acceleration forces: as an example, it should be remembered that when an aircraft flying at 850 km/hour (normal speed for jets) makes a turn with a radius of 1000 m, this causes an acceleration of about 6 g, capable of making the weight of our blood mass only slightly less than that of melted iron. This acceleration is thus incompatible with consciousness when it is exerted in the $+G_z$ direction.

Straight-line accelerations, due to sudden variations in speed of the aircraft (as occurs in catapulting and braking of aircraft on the deck of an aircraft carrier) are not considered very important due to their short duration. It has recently been found that the distant vision is involved, and that the threshold of visual perception is lowered three- or fourfold at 3-5 G; the peripheral acuity is affected more than central acuity, and the effects are additive for repeated accelerations. The experiences of Colonel Stapp, however, have shown that very high straight-line acceleration forces (over 35 g) are relatively well tolerated, although they cause exophthalmos, ecchymoses on the eyelids,and orbital hemorrhages and considerable, although temporary, visual troubles. One retinal detachment occurred at -45 G.

At supersonic speeds, that is at speeds above 1200 km/hour at normal temperature (many military jet planes fly faster than this, as do space vehicles), the problem becomes more serious. At 2000 km/hour, the turning radius must be larger than 8000 m, in order not to cause intolerable gravities. /94

But supersonic speeds involve other problems also, especially when flying through the sound barrier. This is the range between Mach 0.85 and 1.2 (as is known, Mach's wall is the speed of sound, which varies in direct proportion with the absolute temperature; in air, this speed is 1227 km/hour at a temperature of +15°C).

During the passage through this transonic speed range, shock waves, due to rapid air compression, are observed. As is known, zones of discontinuity of air density occur in these waves; they cause instability and turbulence which strongly shake the aircraft. At speeds faster than that of sound, no more difficulties are encountered. This air turbulence has some effect on vision, because it causes visual aberrations; air does in fact become optically more dense, and the wave causes a deviation of light rays and thus an apparent displacement of objects. Pilots thus observe undulation phenomena when going through the sound barrier.

A further difficulty is met by subjects in an aircraft flying at a very high speed. The visual perception may be slower than the occurrence of phenomena that the individual must evaluate. In other words, the "clock" of visual perception is slowed down by a few seconds relative to events taking place (Strughold). In fact, it takes a certain time (a fraction of a second) for an image formed on the retina to go through the optical pathways, reach the cortical visual centers and be worked out, that is, perceived. If impulses for a certain movement must come from this perception, further time will be needed for these impulses to go through the nerves and put into motion the muscles needed to accomplish a certain action. This means that if two aircraft fly at supersonic speed and are in sight of each other (e.g. at 2 km), they will collide before one pilot notices the presence of the other aircraft. If the pilot survives, he will have the perception of the other aircraft /95
after the collision. This makes practically impossible combat between jet planes based on identification without instruments. An aircraft at a distance of 6 km is at the limit of visibility. If two pilots fly toward each other at a speed of 3 Mach, each will have only 3 seconds to identify the enemy plane and locate it before coming into contact with it.

Relative to the psychomotor sensorial reaction time, this is too short a time to allow useful combat activity.

High speeds involve a reduction of the zone in which an object can be perceived in such a way as to elicit a motor response within a useful time. This is a reduction of the size of the visual field, which with increased speeds becomes practically more tubular. Due to this phenomenon, the visual acuity decreases rapidly from the center to the periphery of the visual field.

Even observation of the ground is very difficult at high speeds, and phenomena are observed due to which at first the dimensions decrease, and later objects become larger.

I should like to recall that vibrations also have an effect on visual perception; certain critical frequencies in particular cause a sizeable decrease in visual ability due to resonance phenomena that they cause in the eyeball. Sonic and ultrasonic vibrations (especially sonic ones) may interfere with the visual ability of the subject.

Also in space flights (Gemini V), vibrations took place that prevented the crew, although for a short and noncritical time, from reading the instruments.

Ultrasonic vibrations may also cause changes in the transparency of optical media, and thus a decrease in eyesight.

I shall not mention the importance of air drafts and of outside temperatures caused by fast flight, since these disturbances are practically eliminated by available means of technical protection. In any case, low temperatures and violent wind cause very serious eye lesions, relatively more important than those occurring on the skin.

It should also be pointed out that at high altitudes the /96
harmful effect of solar radiation on the eye increases considerably. The three types of radiation (visible, ultraviolet

and infrared) are all capable of seriously damaging the eye. Visible and infrared solar radiation can cause, besides dazzling and eye fatigue, actual burns of the retina when the pilot must observe the sun to determine his position.

Dazzling has become a special problem in stratospheric flights. At high altitude, the sky becomes less luminous, while the reflection of the underlying clouds causes the zone under the aircraft to become brighter. In rapid ascents, this leads (Whiteside) to an abrupt inversion of the light conditions in the pilot's cabin, relative to the conditions at low altitude, and thus to a different state of adaptation to the light of the lower and higher portions of the retina. This state of adaptation is thus inverted at high altitudes, relative to the one prevalent at low altitudes or on the ground. A change in visual perception of instruments results from this: the instruments appear to be covered by a veil. This phenomenon is made more serious by the great contrast between inside and outside illumination, and by the longer persistence of secondary retinal images of lighted clouds. This persistence is explained by low levels of hypoxia, which take place in spite of the use of oxygen when high altitudes are reached (hypoxia corresponding, e.g. to an altitude of over 3000 m -- when the aircraft is actually at 13,800 m).

Night flight has opened further problems, different for military and civil aviation, which range from the improvement of retinal adaptation ability to techniques of paramacular observation (in order to exploit the higher light sensitivity of the rods) to systems for lighting the cabin containing the flight instruments (in order not to affect the adaptation reached in semidarkness).

Contrary to visible and infrared radiation (which need special defenses), ultraviolet radiation is of less importance in ordinary flight because it is absorbed by the usual means of protection (cabin roof, glass). If it is not absorbed, it causes irritation of the outer parts of the eye.

This fact must, however, be kept in mind, since now there is a tendency to use plexiglas instead of glass for cabin protection. Plexiglas is transparent to ultraviolet radiation, while glass is not. The harmful effects of infrared radiation (heat radiation) on the eye increase with altitude; they can even cause a cataract. As I mentioned above, burns of the retina seem to be caused by infrared radiation, rather than by visible radiation. /97

Space flight poses the problem of ionizing radiation which in space has higher density and energy, due to lack of the protection of the Earth's atmosphere. In the ophthalmological field, the following should be feared: formation of cataracts, bleaching of eyelashes and eyebrows (poliosis) due to enzymatic changes caused by cosmic particles in the cellular organs (capsular epithelium, melanophores of the hair bulb).

Later we shall return in more detail to the ophthalmological problems of space flight and of extraterrestrial life.

The expression "empty visual field" designates (Whiteside) a space in which there are no objects capable of stimulating the focusing of the eye and the accommodation activity. This happens in the dark, when one is surrounded by a dense and uniform fog, or facing a blue, cloudless sky or a completely overcast sky.

Contrary to what one might believe, under these conditions a complete relaxation of accommodation with the eye at rest focused at infinity does not occur; there is instead some accommodation activity, varying between 0.5 and 2 diopters, which causes a myopic state. As a result, the eye becomes focused at 1 or 2 meters, and it is impossible to see distant objects and to focus at infinity. This explains why, in the stratosphere, even in a sky where several aircraft cross each other, the pilot seldom sees them. The accurate work of Whiteside has indicated that, in order to be perceived in an empty visual field, an object must have a size approximately double that permitting it to be seen by an eye adapted to infinity. In other words, at high altitudes an aircraft may be identified by another one only when it is at a distance one-half that permitting it to be seen at low altitude. Thus at high altitudes, the observation of other aircraft is easier for a hypermetropic /98 subject, or for a subject who has lost his accommodation power (presbyopic). The empty visual field also causes a difficulty in the evaluation of distances, dimensions and the speed of objects.

There is also a whole series of visual problems connected with space flight and with the life of man in an extraterrestrial environment, besides those already mentioned (e.g. effects of ionizing radiation on the eye).

I must emphasize that, in spite of the perfection achieved by all the aspects of flight, thanks to more and more efficient and complicated instruments, man's activity, based on visual judgments, will always be an essential factor in any type of mission, even extraterrestrial.

Recently the view has been brought forward that the visual threshold may be lowered by the absence of gravity, and that it is possible for the astronaut to see objects on Earth so small as to subtend an arc smaller than the minimum visible, even after a long stay in a space vehicle. It is, however, possible that an increased sharpness in the perception of certain details (similar to the view supported at the time of the first balloon ascents), observed by some astronauts regarding the Earth (and for which there is an analogy in the behavior of photographic images), may be due only to the apparent effect of atmospheric conditions at different altitudes, for instance to turbulence with dust particles and heterogeneous small bubbles in the atmosphere at stratospheric altitudes; these conditions would not be present at higher altitudes. The view could be entertained that the visual threshold is actually even lower than what is generally believed, when certain obstacles such as those mentioned above are absent.

Experiments carried out during the orbital flight of Gemini V and VII have, however, not succeeded in showing modifications of visual acuity in space flight. In the astronauts of Voshkod 2, the visual efficiency was actually decreased by 20-25%; this was attributed to lack of coordination of eye movements due to the absence of weight. An examination of the oculo-motor activity of Soviet cosmonauts during orbital flight has actually shown some minor disturbances only in some cases (asymmetry of oculo-motor reactions and nystagmoid movements), mostly of a temporary nature.

Deviations in the color vision were also observed, especially /99 for purple, blue and green; the disturbance was very minor for red.

Some people (such as the pilots of Voshkod II, V, VI) have also perceived optical illusion phenomena during orbital flight, such as apparent movements of the dashboard, which others in the same conditions did not notice. Individual factors are certainly of considerable significance, as is shown by the different ability of different subjects to accomplish, during space flight, the "visual egocentric localization of the horizontal"; one subject gave correct answers during all the orbits of Gemini V, and the other subjects made a mistake of over +30° (approximately), relative to the absolute horizontal of his environment.

The absence of weight, on the other hand, independent of altitude, would permit the eye to better discriminate differences of light levels, especially in low light. This has been attributed either to lack of friction, which would allow the eye muscles to effect deviation corrections better, or to effects on the inner ear which would facilitate physiological nystagmus.

Accelerations, on the other hand, have no particular effects on vision during space flights. This is not so for vibrations, as we have already mentioned.

The problems relating to illumination in space flight and in extraterrestrial life are of considerable importance.

The absence of diffuse illumination outside the atmosphere, and the formation of very dark and sharply defined shadows, when certain objects are exposed to almost collimated solar rays, has led to the observation that some three-dimensional solid objects, such as a cube or a pyramid, are percieved as being two-dimensional, i.e., a square or a triangle, respectively.

The estimation of dimensions and of distances is also subject to larger variations under space illumination (larger according to some, smaller according to others) than under diffuse illumination, either in the same subject, or in different subjects. This is particularly important when objects of a type not familiar to the astronaut are observed, especially in the absence of known reference elements, which in this case could only be provided by another space vehicle.

The problem of illumination and of shadows acquires particular importance when the astronaut must go out of his space /100 vehicle to perform certain tasks or missions, such as hooking up of another vehicle, transfer to the other vehicle, repairs, etc. Special lighting equipment can be used here, portable or not, provided by the space craft, especially for shadowy areas. The choice of an appropriate "lengthening" area requires fully efficient visual ability, adequate for this special task.

Passing from strongly lit areas to completely dark areas, and vice versa, understandably also creates difficulties of retinal adaptation.

Special protection with suitable filters is also required against the damaging effects on the retina deriving from looking at the sun in the absence of atmosphere, or also through its accidental presence in the visual field, with strong blinding effects.

Photoreactive filters with optical density instantly variable as a function of the intensity of the light reaching the eye have been studied.

The cosmonauts landing on the lunar surface will also find a "daytime" illumination 20% stronger than on Earth, containing twice as much ultraviolet radiation. Hence come the main effects of dazzling, especially when facing strongly reflective surfaces, with the disturbance of intraretinal irradiation (which may, among other things, cause the dimensions of an object to be evaluated as larger than they actually are) and of greater damage by ultraviolet radiation; adequate protection is particularly needed for these conditions.

On the other hand, "nighttime" illumination on the lunar ground (the "earthlight") in the portion facing the Earth is about 60-80 times stronger than "moonlight" (about 16 lux, instead of 0.20); this illumination makes reading possible and easy.

Also, the very dense shadows projected by the body of the astronaut on the Moon, or by his equipment, will cause difficulties in characterizing instruments or objects. It appears that there may be an increase up to 50% in the time needed to carry out identification tasks under these conditions.

Finally, I should like to remark that the disturbance of "lunar dust" carried by the astronauts on their return into the cockpit of Apollo XII after landing on the Moon (the cockpit was invaded by it on the re-entry voyage) raises the problem of /101 troublesome effects on eye-protection devices, and on the outer parts of the eye itself.

The space available has allowed me to do only a concise review of the main ophthalmological problems met in the field of aviation and space medicine, but I hope that the reader has realized that vision problems have a prominent place in all the aspects of flight. This is fully confirmed by the studies on visual function which have accompanied, and still are accompanying, the programming and carrying out of space flights.